

CRYSTALLINE SEMICONDUCTOR THIN FILM,  
METHOD OF FABRICATING THE SAME,  
SEMICONDUCTOR DEVICE, AND METHOD OF FABRICATING THE  
SAME

BACKGROUND OF THE INVENTION

5 1. Field of the Invention

The present invention relates to a technique on a semiconductor device using a semiconductor thin film, and particularly to a semiconductor device constituted by a thin film transistor (TFT) using a crystalline silicon film and a method of fabricating the same.

10 Incidentally, in the present specification, the term "semiconductor device" means any devices functioning by using semiconductor characteristics. Thus, the semiconductor device includes not only a single semiconductor component such as a TFT, but also an electrooptical device or semiconductor circuit including TFTs and an electronic equipment having those.

15 2. Description of Related Art

In recent years, a TFT used for an electrooptical device such as an active matrix type liquid crystal display device has been actively developed.

20 The active matrix type liquid crystal display device is a monolithic display device in which a pixel matrix circuit and a driver circuit are provided on the same substrate. Moreover, a system-on-panel having a built-in logic circuit such as a  $\gamma$ -correction circuit, a memory circuit, and a clock generating circuit has been also developed.

25 Since such a driver circuit and a logic circuit are required to perform a high speed operation, it is unsuitable to use a noncrystalline silicon film (amorphous silicon film) as an active layer. Thus, under the present circumstances, a TFT using a crystalline silicon film (single crystal silicon film or polysilicon film) as an active layer has been examined.

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The present assignee has Japanese Patent Application Laid-open No. Hei. 7-130652 disclosing a technique for obtaining a crystalline silicon film on a glass substrate. The technique disclosed in the publication is such that a catalytic element for facilitating crystallization is added into an amorphous silicon film, and a heat treatment is carried out to obtain a crystalline silicon film. The entire disclosure of this patent is incorporated herein by reference.

According to this technique, it is possible to greatly lower the crystallization temperature of the amorphous silicon film through the action of the catalytic element by 50 to 100°C, and is also possible to decrease a time required for crystallization down to 1/5 to 1/10.

However, when circuit performance comparable to a conventional LSI comes to be required for a circuit assembled with TFTs, such circumstances have occurred that it is difficult to fabricate a TFT having satisfactory performance to meet the specification by using a crystalline silicon film formed with a conventional technique.

Incidentally, in the present specification, a semiconductor thin film having crystallinity, such as a single crystal semiconductor thin film, a polycrystalline semiconductor thin film, and a microcrystalline semiconductor thin film, is generically referred to as a crystalline semiconductor thin film.

#### SUMMARY OF THE INVENTION

An object of the present invention is to provide a technique for forming a crystalline semiconductor film to form a semiconductor component having more excellent characteristics.

According to an aspect of the present invention, a method of fabricating a crystalline semiconductor thin film is characterized by comprising the steps of: carrying out a first heat treatment to transform an amorphous semiconductor thin film into a crystalline semiconductor thin film by irradiating an ultraviolet light or infrared light; and carrying out a second heat treatment for the crystalline semiconductor

thin film at 900 to 1200°C in a reduced atmosphere.

In the above structure, the second heat treatment has to be carried out at such a temperature that a natural oxidation film (for example, silicon oxide film) formed on the surface of the crystalline semiconductor thin film can be reduced, and is specifically carried out in a temperature range of 900 to 1200°C (preferably 1000 to 1100°C). Besides, it is preferable that a treatment time is at least 3 minutes or more, typically 3 minutes to 2 hours, and representatively 10 minutes to 30 minutes. This is a time required to exhibit effects of the second heat treatment.

Incidentally, the second heat treatment may be carried out after the crystalline semiconductor thin film is converted into island-like portions. Besides, the heat treatment is carried out by furnace annealing (annealing carried out in an electrothermal furnace).

The feature of the present invention is that a crystalline semiconductor thin film is first formed by using a technique of crystallization by irradiating an ultraviolet light or infrared light (hereinafter referred to as laser crystallization), and the crystalline semiconductor thin film is subjected to the heat treatment at 900 to 1200°C in the reduced atmosphere (typically, hydrogen atmosphere).

In this case, when ultraviolet light is used, it is appropriate that excimer laser light or strong light emitted from an ultraviolet lamp is used as a crystallization technique, and when infrared light is used, it is appropriate that strong light emitted from an ultraviolet laser or an infrared lamp is used.

As the excimer laser light, it is appropriate that KrF, XeCl, ArF or the like is used for an excitation gas. Further, as the infrared light, Nd: YAG laser, Nd: glass laser, ruby laser or the like may be used.

The beam of the laser light may be formed to have a linear or planar cross section. When the beam is a line-shaped beam, such a laser that scans a laser light from one end of the substrate toward the other end thereof is preferably used.

Further, when the beam is a planar beam, the area of about several tens  $\text{cm}^2$  (preferably, 10  $\text{cm}^2$  or more) can be irradiated at one time, and it is appropriate that a laser having a total output energy of 5 J or more, preferably 10 J or more, is used. In this case, it is preferable that the density of energy is 100 to 800  $\text{mJ}/\text{cm}^2$ , and the output pulse width is 100 nsec or more, preferably 200 nsec to 1 msec. For the purpose of realizing the pulse width of 200 nsec to 1 msec, it is appropriate that a plurality of lasers are connected to one another and synchronization of the lasers are shifted to create a state where plural pulses are mixed.

Incidentally, high temperature annealing in a reduced atmosphere which is carried out for the crystalline semiconductor thin film that has been crystallized has an effect to flatten the surface of the crystalline semiconductor thin film. This is a result of enhanced surface diffusion of semiconductor atoms to make the surface energy minimum.

The effect of flattening is very effective in the case where the crystalline film is irradiated with excimer laser ultraviolet light. When irradiation of excimer laser is done, the semiconductor film is instantaneously melted from its surface, and then, the melted semiconductor film is cooled and solidified from a substrate side by heat conduction to the substrate. In this solidifying step, the melted semiconductor film is recrystallized, and becomes a crystalline semiconductor thin film with a large grain diameter. However, since the film is once melted, volume expansion occurs so that asperities (ridges) are produced on the surface of the semiconductor film. In the case of a top gate type TFT, since the surface having the asperities becomes an interface to a gate insulating film, the component characteristics are greatly affected.

#### BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

Figs. 1A to 1F are views showing fabricating steps of a thin film

transistor;

Figs. 2A to 2C are views showing the structures of electrooptical devices;

5 Figs. 3A to 3F and 4A to 4D are views showing the structure of an electronic equipment;

Fig. 5 shows statistical data of bearing ratios at 1/2 of P-V;

Fig. 6 is a characteristic view of a thresholdless antiferroelectric mixed liquid crystal;

10 Fig. 7 is a SEM observation photograph of the surface of a crystalline silicon film before high temperature annealing;

Fig. 8 is a SEM observation photograph of the surface of the crystalline silicon film after high temperature annealing;

Fig. 9 is an AFM image of the surface of a crystalline silicon film before high temperature annealing;

15 Fig. 10 is a AFM image of the surface of the crystalline silicon film after high temperature annealing;

Fig. 11 is a histogram distribution and a bearing ratio curve of the height of an AFM image before high temperature annealing;

20 Fig. 12 is a histogram distribution and a bearing ratio curve of the height of the AFM image after high temperature annealing; and

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

First, by using experimental results obtained by the present inventor, an effect of high temperature annealing of the present invention will be described.

25 An experimental procedure will first be explained. An amorphous silicon film with a thickness of 50 nm was formed on a quartz substrate. A low pressure CVD method was used for film formation, and disilane ( $\text{Si}_2\text{H}_6$ ) (flow rate: 250 sccm) and helium (He) (flow rate: 300 sccm) were used as film forming gases. The temperature of the substrate was made  
30 465°C and the pressure at film formation was made 0.5 torr.

The surface of the amorphous silicon film was etched by buffered

hydrofluoric acid to remove a natural oxidation film and pollution. Next, the amorphous silicon film was irradiated with XeCl excimer laser light to be crystallized. An atmosphere of the laser irradiation was the air, and the substrate temperature was room temperature, the density of laser energy was 400 mJ/cm<sup>2</sup>, and the pulse width of the laser light was 150 nsec.

Then the crystalline silicon film was subjected to a high temperature annealing treatment. The condition of the high temperature annealing treatment was made as follows: An atmosphere was made hydrogen of 100%, the degree of vacuum was 700 torr, annealing temperature was 1000°C, and an annealing time was 25 minutes. Incidentally, before the high temperature annealing treatment, the crystalline silicon film was subjected to a wet etching treatment by hydrofluoric acid, so that a natural oxidation film and pollution on the surface were removed.

For the purpose of ascertaining the effect of the high temperature annealing, the surface of the crystalline silicon film before and after the high temperature annealing was observed by SEM. Fig. 7 shows an observation photograph before the high temperature annealing, and Fig. 8 shows an observation photograph after the high temperature annealing. As is apparent from Figs. 7 and 8, the surface shapes are clearly different before and after the high temperature annealing.

Further, the surface shape of the silicon film was also observed by an AFM (Atomic Force Microscope). Fig. 9 shows an observation image of the crystalline silicon film by the AFM before the high temperature annealing, and Fig. 10 shows an observation image of the crystalline silicon film by the AFM after the high temperature annealing. Incidentally, the range of observation is a rectangular region of 1.5 μm x 1.5 μm in both Figs. 9 and 10.

As is apparent from Figs. 9 and 10, the surface shapes of the crystalline silicon film before and after the high temperature annealing

are clearly different. Although asperities exist on the surface of the crystalline silicon film before and after the high temperature annealing, before the high temperature annealing, a protrusion is steep, and its top portion is sharp, and the surface totally shows a serrate shape. When the surface having such protrusions becomes an interface between a gate insulating film and a channel formation region, it is thinkable that the component characteristics suffer a very bad influence. On the contrary, a protrusion after the high temperature annealing is smooth, and its top portion is round, so that the characteristics of the interface between the gate insulating film and the channel formation region are improved as compared with those before the high temperature annealing.

Although it is understood that the surface of the crystalline silicon film is flattened and smoothed even from the observation of images shown in Figs. 7 to 10, a histogram distribution of heights of AFM images was calculated so as to further quantify the difference of the surface shapes before and after the high temperature annealing. Further, a bearing ratio curve of the histogram distribution was calculated. The bearing ratio curve is a curve expressing a cumulative frequency of the histogram distribution.

Figs. 11 and 12 show the histogram of the heights of the AFM images and the bearing ratio curve. Fig. 11 shows data before the high temperature annealing, and a pitch of the histogram is about 0.16 nm. Fig. 12 shows data after the high temperature annealing, and a pitch of the histogram is about 0.20 nm.

The measurement region by the AFM is  $1.5 \mu\text{m} \times 1.5 \mu\text{m}$ . The bearing ratio curve is a curve expressing the cumulative frequency of data of the histogram. The curves of Figs. 11 and 12 are obtained through accumulation from the maximum value of the height, and expresses an occupation ratio (%) of areas with height from the maximum value to an arbitrary value to the total area. In Figs. 11 and 12, the horizontal line shown by a dotted line in the graph indicates the

value of  $1/2$  of the P-V value (Peak to Valley, difference between the maximum value and the minimum value in height).

Further, in the silicon film before and after the high temperature annealing, the AFM images were observed in ten regions (rectangle region of  $1.5 \mu\text{m} \times 1.5 \mu\text{m}$ ), and the bearing ratios at  $2^{-1}$  (P-V value) in the respective observation regions were calculated. Fig. 5 shows the bearing ratios in the respective observation regions and their statistical data.

When the curves in Figs. 11 and 12 are compared with each other, although the height distribution before the high temperature annealing is inclined toward a low portion side, the inclination is shifted toward a high portion side after the high temperature annealing, and the histogram is symmetrical with respect to the position of  $1/2$  of the P-V. This can be easily understood from the bearing ratio curve.

The bearing ratio at the height of  $2^{-1}$ (P-V) is about 20 % in Fig. 11, and about 51% in Fig. 12. That is, an occupation ratio of an area of a region where the height is within the range from the maximum value to  $2^{-1}$ (P-V value) to the total area is about 20% before the high temperature annealing, and about 51% after the high temperature annealing. From the difference in this ratio as well, it can be understood that the sharp top portion has been rounded and the surface of the silicon film has been flattened by the high temperature annealing.

In the present invention, the surface shape of the crystalline silicon film is quantified by the bearing ratio at  $2^{-1}$ (P-V value), and from experimental results, it is presumed that the bearing ratio at  $2^{-1}$ (P-V value), that is, in a predetermined observation region, an occupation ratio of a region where the height exists in the range from the maximum value to  $2^{-1}$ (P-V value) is within the range of 6 to 28% in the film before the high temperature annealing, and 29 to 72% in the film after the high temperature annealing.

Incidentally, the range of the bearing ratio is set from the statistical data of Fig. 5, and is a value calculated from an average value



±3σ of the bearing ratio at 2-1(P-V value) . The bearing ratio is a value accumulated from the maximum value of the height.

As described above, since the crystalline semiconductor thin film crystallized by ultraviolet light such as excimer laser light is crystallized after the surface has been melted, the occupying ratio of a region where the height is within the range from the maximum value to 1/2 of the difference between the maximum value and the minimum value is 6 to 28% to a predetermined region. In the present invention, since this crystalline semiconductor thin film is subjected to the high temperature annealing, the occupation ratio of this region is changed to 29 to 72%, and the top portion of the protrusion of the film surface can be made smooth.

This step has also an effect to greatly decrease defects existing in crystal grains and crystal grain boundaries. This effect is obtained through a terminating effect of uncombined bonds by hydrogen, a removing effect of impurities by hydrogen, and recombination of semiconductor atoms with the effect. Thus, for the purpose of causing these effects to be effectively exhibited, the treatment time as set forth above becomes necessary.

Thus, it is necessary to carry out the heat treatment step in the reduced atmosphere by furnace annealing. If the heat treatment is carried out by irradiation of ultraviolet light or infrared light, recrystallization progresses in a nonequilibrium state so that continuity of crystal lattices at crystal grain boundaries is damaged, which is not preferable. In this point, in the furnace annealing, since recrystallization progresses in an equilibrium state, such a problem can be avoided.

According to another aspect of the present invention, the method of the present invention is characterized by comprising the steps of:

forming an amorphous semiconductor thin film on a substrate having an insulating surface;

carrying out a first heat treatment to transform the amorphous semiconductor thin film into a crystalline semiconductor thin film by

irradiating ultraviolet light or infrared light;

carrying out a second heat treatment for the crystalline semiconductor thin film in a reduced atmosphere including a halogen element; and

5 prior to the step of forming the amorphous semiconductor thin film, adding a catalytic element for facilitating crystallization of the amorphous semiconductor thin film to the substrate having the insulating surface.

10 In such an arrangement, the second heat treatment is carried out at a temperature range of 900 to 1200°C. This step aims at a gettering function of the halogen element to a metal element, and has an object to remove as halogen compound the metal element existing in a crystalline semiconductor thin film.

15 In the following, preferred embodiments of the present invention will be described in detail.

#### [Embodiment 1]

In this embodiment, the steps of fabricating a TFT on a substrate in accordance with the present invention will be described. A description will be made with reference to Fig. 1.

20 First, a quartz substrate was prepared as a substrate 101. A material having high heat resistance must be selected as the substrate 101. Instead of the quartz substrate, a substrate of a material having high heat resistance, such as a silicon substrate, a ceramic substrate, or a crystallized glass substrate, may be used.

25 However, although an under film may not be provided in the case where the quartz substrate is used, it is preferable to provide an insulating film as the under film in the case where other materials are used. As an insulating film, it is appropriate that either one of a silicon oxide film (SiOx), a silicon nitride film (SixNy), a silicon nitride oxide film (SiOxNy), and an aluminum nitride film (AlxNy), or a laminate film of  
30 those is used.

Besides, it is effective to use an under film laminate a refractory

metal layer and a silicon oxide film since a heat radiation effect is greatly increased. Even the laminate structure of the foregoing aluminum nitride film and the silicon oxide film exhibits a sufficient heat radiation effect.

5 After the substrate 101 having the insulating surface was prepared in this way, a crystalline silicon film with a thickness of 30 nm was formed by using a crystallization technique using a excimer laser. Only the outline will be described in the present embodiment.

10 For the purpose of forming an amorphous silicon film, in this embodiment, disilane ( $\text{Si}_2\text{H}_6$ ) was used as a film forming gas. An amorphous silicon film (not shown) with a thickness of 20 to 60 nm was formed by a low pressure CVD method. At this time, it is important to thoroughly control the concentration of impurities, such as C(carbon), N(nitrogen), and O(oxygen) mixed in the film. This is because if the  
15 amount of these impurities is high, the progress of crystallization is prevented.

20 The applicant controlled the impurity concentration so that the concentration of carbon and nitrogen became  $5 \times 10^{18}$  atoms/cm<sup>3</sup> or less (preferably  $1 \times 10^{18}$  atoms/cm<sup>3</sup> or less, more preferably,  $5 \times 10^{17}$  atoms/cm<sup>3</sup> or less, further more preferably  $2 \times 10^{17}$  toms/cm<sup>3</sup>), the concentration of oxygen became  $1.5 \times 10^{19}$  atoms/cm<sup>3</sup> or less (preferably  $5 \times 10^{18}$  atoms/cm<sup>3</sup> or less, more preferably  $1 \times 10^{18}$  atoms/cm<sup>3</sup>). Further, control was made so that the concentration of  
25 metal elements became  $1 \times 10^{17}$  atoms/cm<sup>3</sup> or less. When such control of concentration has been made at a film formation stage, if only external pollution is prevented, impurity concentration is not increased during the steps of fabricating a TFT.

30 After the amorphous silicon film was formed, dehydrogenation was carried out for about one hour at 450°C, and thereafter the step of crystallizing the amorphous silicon film was carried out using XeCl excimer laser light excited by the X-ray (second heat treatment). In this embodiment, the area of the laser irradiation was 10 cm x 10 cm, the

density of laser energy was 300 mJ/cm<sup>2</sup>, and the pulse width of the laser light was 150 nsec. A crystalline silicon film 102 was thus obtained (Fig. 1A).

Incidentally, if film quality equal to the amorphous silicon film formed by the reduced pressure CVD method may be obtained, a plasma CVD method may be used. Instead of the amorphous silicon film, an amorphous semiconductor thin film such as a film of silicon germanium (expressed by Si<sub>x</sub>Ge<sub>1-x</sub> (0 < X < 1)) in which germanium is contained in an amorphous silicon film may be used. In that case, it is desirable that germanium contained in silicon germanium is made 5 atomic% or less.

Next, a heat treatment within a temperature range of 900 to 1200°C (preferably 1000 to 1150°C) was carried out in a reduced atmosphere. In this embodiment, a heat treatment at 1050°C for 20 minutes was carried out in a hydrogen atmosphere (Fig. 1C). As a result, the occupying ratio of a region where the height is within the range from the maximum value to 1/2 of the difference between the maximum value and the minimum value can be 29 to 72% (Fig. 1B).

As the reduced atmosphere, although a hydrogen atmosphere, an ammonia atmosphere, or an inert gas atmosphere containing hydrogen or ammonia (mixture atmosphere of hydrogen and nitrogen or hydrogen and argon) is desirable, flattening of the surface of the crystalline silicon film can be made by even the inert gas atmosphere. However, if reduction of a natural oxidation film is carried out by using a reducing function, a number of silicon atoms with high energy are produced and the flattening effect is consequently raised, so that the reduced atmosphere is preferable.

However, attention must be paid especially to a point that the concentration of oxygen or oxygen compound (for example, OH group) contained in the atmosphere is made 10 ppm or less (preferably 1 ppm or less). Otherwise, the reducing reaction by hydrogen may not occur sufficiently.

In this way, a crystalline silicon film 103 was obtained. The

surface of the crystalline silicon film 103 was greatly flattened by a hydrogen heat treatment at a high temperature such as 900 to 1200°C. Besides, since the heat treatment was carried out at a high temperature, lamination defects and the like hardly existed in the crystal grains.

5 After the crystalline silicon film 103 was obtained in this way, the crystalline silicon film 103 was next patterned to form an active layer 104. In this embodiment, although the heat treatment in the hydrogen atmosphere is carried out before the active layer 111 is formed, the heat treatment may be carried out after the active layer is  
10 formed. In the case, it is preferable that since patterning has been made, stress generated in the crystalline silicon film is relieved.

Then a thermal oxidation step was carried out so that a silicon oxide film 105 with a thickness of 10 nm was formed on the surface of the active layer 104. This silicon oxide film 105 functions as a gate  
15 insulating film. Besides, since the film thickness of the active layer 104 was decreased by 5 nm, the film thickness became 30 nm. In view of the film decrease by the thermal oxidation, it is necessary to determine the film thickness of the amorphous silicon film (starting film) so that an active layer 111 (especially a channel formation region) with a thickness  
20 of 5 to 40 nm finally remains.

After the gate insulating film 105 was formed, a polycrystalline silicon film having conductivity was formed thereon and a gate wiring line 106 was formed by patterning (Fig. 1C).

In this embodiment, although the polycrystalline silicon film  
25 having N-type conductivity is used as the gate wiring line, a material is not limited to this. Particularly, for the purpose of lowering the resistance of the gate wiring line, it is also effective to use tantalum, tantalum alloy, or laminate film of tantalum and tantalum nitride. Further, in order to attain a gate wiring line with low resistance, it is  
30 also effective to use copper or copper alloy.

After the state of Fig. 1C was obtained, an impurity to give N-type conductivity or P-type conductivity was added to form an impurity

region 107. The impurity concentration at this time was determined in view of an impurity concentration of a subsequent LDD region. In this embodiment, although arsenic with a concentration in  $1 \times 10^{18}$  atoms/cm<sup>3</sup> was added, it is not necessary to limit the impurity and the concentration to those of this embodiment.

Next, a thin silicon oxide film 108 with a thickness of about 5 to 10 nm was formed on the surface of the gate wiring line 106. It is appropriate that this film is formed by using a thermal oxidation method or a plasma oxidation method. The formation of this silicon oxide film 108 has an object to cause the film to function as an etching stopper in a subsequent side wall forming step.

After the silicon oxide film 108 that functions as an etching stopper was formed, a silicon nitride film was formed and etch back was carried out, so that a side wall 109 was formed. In this way, the state of Fig. 1D was obtained.

Incidentally, in this embodiment, although the silicon nitride film was used as the side wall, it is also possible to use a polycrystalline silicon film or an amorphous silicon film. Of course, it is needless to say that if a material of the gate wiring line is changed, a material which can be used as the side wall is also changed according to that.

Next, an impurity with the same conductivity as that in the previous step was again added. The concentration of the impurity added at this time was made higher than that in the previous step. In this embodiment, although arsenic is used as an impurity and its concentration is made  $1 \times 10^{21}$  atoms/cm<sup>3</sup>, it is not necessary to make limitation to this. By the adding step of the impurity, a source region 110, a drain region 111, an LDD region 112, and a channel formation region 113 were defined (Fig. 1E).

After the respective impurity regions were formed in this way, activation of the impurity was carried out by a heat treatment such as furnace annealing, laser annealing, or lamp annealing.

Next, silicon oxide films formed on the surfaces of the gate wiring

line 106, the source region 110, and the drain region 111 were removed to expose the surfaces of those. Then a cobalt film (not shown) with a thickness of about 5 nm was formed and a heat treatment step was carried out. A reaction of cobalt and silicon occurred by this heat treatment, so that a silicide layer (cobalt silicide layer) 114 was formed (Fig. 1F).

This technique is a well-known silicide technique. Thus, instead of cobalt, titanium or tungsten may be used, and a heat treatment condition and the like may be determined by referring to a well-known technique. In this embodiment, the heat treatment step was carried out by irradiation of infrared light.

After the silicide layer 114 was formed in this way, the cobalt film was removed. Thereafter, an interlayer insulating film 115 with a thickness of 1  $\mu\text{m}$  was formed. As the interlayer insulating film 115, it is appropriate that a silicon oxide film, a silicon nitride film, a silicon nitride oxide film, or a resin film (polyimide, acryl, polyamide, polyimidoamide, benzocyclobutene (BCB), etc.) is used. These insulating films may be laminated in a free combination.

Next, contact holes were formed in the interlayer insulating film 115, and a source wiring line 116 and a drain wiring line 117 made of a material containing aluminum as its main ingredient were formed. Finally, the whole component was subjected to furnace annealing at 300°C for 2 hours in a hydrogen atmosphere, so that hydrogenating was completed.

A TFT as shown in Fig. 1F was obtained in this way. Incidentally, the structure explained in this embodiment is merely an example, and a TFT structure to which the present invention can be applied is not limited to this. The present invention can be applied to a TFT of any well-known structure. Besides, it is not necessary to limit numerical value conditions in steps subsequent to formation of the crystalline silicon film 103 to those of this embodiment. Further, there is no problem if a well-known channel doping step (impurity adding step for

controlling a threshold voltage) is introduced to somewhere in this embodiment.

Besides, in this embodiment, since the concentration of impurities such as C, N, and O was thoroughly controlled at the stage of film formation of the amorphous silicon film as the starting film, the concentration of each impurity contained in the active layer of the completed TFT was such that the concentration of carbon and nitrogen remained to be  $5 \times 10^{18}$  atoms/cm<sup>3</sup> or less (preferably  $1 \times 10^{18}$  atoms/cm<sup>3</sup> or less, more preferably  $5 \times 10^{17}$  /cm<sup>3</sup> or less, further more preferably  $2 \times 10^{17}$  cm<sup>-3</sup> or less), and the concentration of oxygen remained to be  $1.5 \times 10^{19}$  atoms/cm<sup>3</sup> or less (preferably  $5 \times 10^{18}$  atoms/cm<sup>3</sup> or less, more preferably  $1 \times 10^{18}$  cm<sup>-3</sup> or less). The concentration of metal elements was  $1 \times 10^{17}$  atoms/cm<sup>3</sup> or less.

Besides, the present invention can be applied to not only a top gate structure but also to a bottom gate structure typified by a reverse stagger TFT.

Although the description has been made on the N-channel TFT as an example, it is also easy to fabricate a P-channel TFT through combination with a well-known technique. Further, through combination with a well-known technique, it is also possible to form a CMOS circuit by fabricating an N-channel TFT and a P-channel TFT on the same substrate and by complementarily combining them.

Further, in the structure of Fig. 1F, if a pixel electrode (not shown) electrically connected to the drain wiring line 117 is formed by a well-known means, it is also easy to form a pixel switching element of an active matrix type display device. U.S. Patent No. 5,712,495 issued to Suzawa is an example for showing a structure of an active matrix device. An entire disclosure of this patent is incorporated herein by reference. It is also preferable to use an LDD TFT as a switching transistor for a pixel.

The present invention can be also carried out when an active matrix type electrooptical device such as a liquid crystal display device

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or an EL (electroluminescence) display device is fabricated.

[Embodiment 2]

In this embodiment, the case will be described where the step of removing a metal element in the film is used together with the step of hydrogen annealing at 900 - 1200°C according to the embodiment 1.

In this embodiment, a heat treatment was carried out at 900 to 1200°C in the atmosphere where 0.1 to 5 wt% of hydrogen halide (typically, hydrogen chloride) is combined in the hydrogen atmosphere. Besides,  $\text{NF}_3$  or  $\text{HBr}$  may be used as hydrogen halide.

By adopting this embodiment, it is possible to remove or lower a metal element from the crystalline silicon film. Since the concentration of the metal element is lowered down to  $1 \times 10^{17}$  atoms/cm<sup>3</sup> or less, it is possible to prevent TFT characteristics (especially off current value) from fluctuating by the existence of the metal element.

[Embodiment 3]

In this embodiment, an example of a reflection-type liquid crystal display device fabricated according to the present invention is shown in Figs. 2A to 2C. Since well-known means may be used for a fabricating method of a pixel TFT (pixel switching element) and for a cell assembling step, their detailed descriptions will be omitted.

In Fig. 2A, reference numeral 11 denotes a substrate (ceramic substrate provided with a silicon oxide film) having an insulating surface, 12 denotes a pixel matrix circuit, 13 denotes a source driver circuit, 14 denotes a gate driver circuit, 15 denotes an opposite substrate, 16 denotes an FPC (Flexible Printed Circuit), and 17 denotes a signal processing circuit. As the signal processing circuit 17, a circuit for carrying out such processing that an IC has been substituted, such as a D/A converter, a  $\gamma$ -correction circuit, and a signal dividing circuit, can be formed. These circuits are desirably constituted with TFTs in accordance with the present invention. In an alternative, it is also possible to provide an IC chip on a glass substrate and to carry out signal processing on the IC chip.

Moreover, although the description has been made of the liquid crystal display device as an example, the present invention can also be applied to an EL (electroluminescence) display device or an EC (electrochromic) display device as long as the device is an active matrix type display device.

Here, an example of a circuit constituting the driver circuits 13 and 14 of Fig. 2A is shown in Fig. 2B. Since the TFT portion has been explained in the embodiment 1, only necessary portions will be described here.

In Fig. 2B, reference numerals 501 and 502 denote N-channel TFTs, and 503 denotes a P-channel TFT. The TFTs 501 and 503 constitute a CMOS circuit. Reference numeral 504 denotes an insulating layer made of a laminate film of a silicon nitride film/a silicon oxide film/a resin film. A titanium wiring line 505 is provided thereon, and the foregoing CMOS circuit and the TFT 502 are electrically connected. The titanium wiring line is covered with an insulating layer 506 made of a resin film. The two insulating layers 504 and 506 have also a function as a flattened film.

A part of a circuit constituting the pixel matrix circuit 12 of Fig. 2A is shown in Fig. 2C. In Fig. 2C, reference numeral 507 denotes a pixel TFT made of an N-channel TFT of double gate structure, and a drain wiring line 508 is formed so as to widely extend in a pixel region. Incidentally, other than the double gate structure, a single gate structure, a triple gate structure, or the like may be used.

An insulating layer 504 is provided thereon, and a titanium wiring line 505 is provided thereon. At this time, a recess portion is formed in a part of the insulating layer 504, and only silicon nitride and silicon oxide on the lowermost layer are made to remain. By this, an auxiliary capacitance is formed between the drain wiring line 508 and the titanium wiring line 505.

The titanium wiring line 505 provided in the pixel matrix circuit has an electric field shielding effect between source/drain wiring lines

and a subsequent pixel electrode. Further, it also functions as a black mask at a gap between a plurality of pixel electrodes.

Then an insulating layer 506 is provided to cover the titanium wiring line 505, and a pixel electrode 509 made of a reflective conductive film is formed thereon. Of course, contrivance for increasing reflectivity may be made to the surface of the pixel electrode 509.

By using the present invention, it is possible to fabricate the reflection-type liquid crystal display device having the structure as described above. Of course, when a well-known technique is combined, a transmission-type liquid crystal display device can also be fabricated. Further, when a well-known technique is combined, an active matrix type EL display device can also be easily fabricated.

Although not distinguished in the drawings, it is also possible to make the film thicknesses of gate insulating films different between the pixel TFT constituting the pixel matrix circuit and the CMOS circuit constituting the driver circuit and the signal processing circuit.

In the pixel matrix circuit, since a driving voltage applied to the TFT is high, the gate insulating film with a film thickness of 50 to 200 nm is required. On the other hand, in the driver circuit and the signal processing circuit, a driving voltage applied to the TFT is low, while high speed operation is required. Thus, it is effective to make the film thickness of the gate insulating film about 3 to 30 nm, which is thinner than that of the pixel TFT.

#### [Embodiment 4]

In the liquid crystal display device fabricated in the above embodiment, other than a TN liquid crystal, various liquid crystals may be used. For example, it is possible to use a liquid crystal disclosed in "Characteristics and Driving Scheme of Polymer-Stabilized Monostable FLCD Exhibiting Fast Response Time and High Contrast Ratio with Gray-Scale Capability" by H. Furue et al. 1998 SID, "A Full-Color Thresholdless Antiferroelectric LCD Exhibiting Wide Viewing Angle with Fast Response Time" by T. Yoshida et al., 1997, SID DIGEST, 841, "Thresholdless

antiferroelectricity in liquid crystals and its application to displays" by S. Inui et al., 1996, J. Mater. Chem. 6(4), 671-673, or US Patent No. 5,594,569.

5 A liquid crystal exhibiting antiferroelectricity in some temperature range is called an antiferroelectric liquid crystal. In mixed liquid crystals including antiferroelectric liquid crystals, there is a thresholdless antiferroelectric mixed liquid crystal exhibiting electrooptical response characteristics in which transmittance is continuously changed with respect to an electric field. Some  
10 thresholdless antiferroelectric mixed liquid crystal exhibits V-shaped electrooptical response characteristics, and the liquid crystal in which its driving voltage is about  $\pm 2.5$  V (cell thickness is about  $1\text{ }\mu\text{m}$  to  $2\text{ }\mu\text{m}$ ) has also been found.

15 Here, Fig. 6 shows an example of characteristics of light transmittance of the thresholdless antiferroelectric mixed liquid crystal showing the V-shaped electrooptical response to applied voltage. The vertical axis of the graph shown in Fig. 6 indicates the transmittance (in arbitrary unit) and the horizontal axis indicates the applied voltage. Incidentally, the transmission axis of a polarizing plate of a liquid  
20 crystal display device at an incident side is set almost parallel to a normal direction of a smectic layer of the thresholdless antiferroelectric mixed liquid crystal which is almost coincident with a rubbing direction of the liquid crystal display device. The transmission axis of the polarizing plate at an outgoing side is set almost normal (crossed Nicols)  
25 to the transmission axis of the polarizing plate at the incident side.

As shown in Fig. 6, it is understood that when such a thresholdless antiferroelectric mixed liquid crystal is used, low voltage driving and gradation display become possible.

30 In the case where such a low voltage driving thresholdless antiferroelectric mixed liquid crystal is used for a liquid crystal display device having an analog driver, it becomes possible to suppress the source voltage of a sampling circuit of an image signal to, for example,

about 5 V to 8 V. Thus, the operation source voltage of the driver can be lowered, and low power consumption and high reliability of the liquid crystal display device can be realized.

5 Also in the case where such a low voltage driving thresholdless antiferroelectric mixed liquid crystal is used for a liquid crystal display device having a digital driver, an output voltage of a D/A conversion circuit can be lowered, so that the operation source voltage of the D/A conversion circuit can be lowered and the operation source voltage of the driver can be made low. Thus, low power consumption and high  
10 reliability of the liquid crystal display device can be realized.

Thus, to use such a low voltage driving thresholdless antiferroelectric mixed liquid crystal is also effective in the case where a TFT having an LDD region (low concentration impurity region) with a relatively small width (for example, 0 nm to 500 nm or 0 nm to 200  
15 nm) is used.

In general, the thresholdless antiferroelectric mixed liquid crystal has large spontaneous polarization, and the dielectric constant of the liquid crystal itself is high. Thus, in the case where the thresholdless antiferroelectric mixed liquid crystal is used for a liquid crystal display device, it becomes necessary to provide relatively large holding capacitance for a pixel. Thus, it is preferable to use the thresholdless antiferroelectric mixed liquid crystal having small spontaneous polarization. Besides, it is also permissible to design such that a driving  
20 method of the liquid crystal display device is made linear sequential driving, so that a writing period (pixel feed period) of a gradation voltage to a pixel is prolonged and holding capacitance is compensated even if it is small.

Since low voltage driving can be realized by using such a thresholdless antiferroelectric mixed liquid crystal, low power  
30 consumption of the liquid crystal display device can be realized.

Incidentally, as long as a liquid crystal has electrooptical characteristics as shown in Fig. 6, any liquid crystal can be used as a

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display medium of a liquid crystal display device of the present invention.

[Embodiment 5]

5 The CMOS circuit or pixel matrix circuit formed by implementing the present invention can be used for a variety of electrooptical devices (such as active matrix type liquid crystal display, active matrix type EL display, and active matrix type EC display). That is, the present invention can be implemented by any electronic equipment equipped with these electrooptical devices as display media.

10 Such electronic equipments include a video camera, a digital camera, a (rear-type or front-type) projector, a head mount display (goggle type display), a car navigation system, a personal computer, and a portable information terminal (mobile computer, cellular phone or electronic book, etc.). Figs. 3A to 3F and 4A to 4D depict examples of these equipments.

15 Fig. 3A depicts a personal computer that is constituted by a main body 2001, an image input portion 2002, a display device 2003, and a keyboard 2004. The present invention can be applied to the image input portion 2002, the display device 2003, and other signal control circuits.

20 Fig. 3B depicts a video camera that is constituted by a main body 2101, a display device 2102, an audio input portion 2103, an operation switch 2104, a battery 2105, and an image receiving portion 2106. The present invention can be applied to the display device 2102, the audio input portion 2103, and other signal control circuits.

25 Fig. 3C depicts a mobile computer that is constituted by a main body 2201, a camera unit 2202, an image receiving portion 2203, an operation switch 2204, and a display device 2205. The present invention can be applied to the display device 2205 and other signal control circuits.

30 Fig. 3D depicts a goggle type display that is constituted by a main body 2301, a display device 2302, and an arm portion 2303. The present invention can be applied to the display device 2302 and other

signal control circuits.

Fig. 3E depicts a player using a recording medium with a recorded program (hereinafter referred to as recording medium), that is constituted by a main body 2401, a display device 2402, a speaker unit 2403, a recording medium 2404, and an operation switch 2405. Incidentally, this apparatus uses a DVD (Digital Versatile Disc), a CD, and the like as the recording medium, and it is possible to appreciate music, to appreciate a movie, to play a game, and to perform the Internet. The present invention can be applied to the display device 2402 and other signal control circuits.

Fig. 3F depicts a digital camera that is constituted by a main body 2501, a display device 2502, an eyepiece portion 2503, an operation switch 2504, and an image receiving portion (not shown). The present invention can be applied to the display device 2502 and other signal control circuits.

Fig. 4A depicts a front type projector that is constituted by a display device 2601, and a screen 2602. The present invention can be applied to the display device 2601 and other signal control circuits.

Fig. 4B depicts a rear type projector that is constituted by a main body 2701, a display device 2702, a mirror 2703, and a screen 2704. The present invention can be applied to the display device 2702 and other signal control circuits.

Fig. 4C shows an example of the structure of the display devices 2601, 2702 shown in Figs. 4A and 4B. The display devices 2601, 2702 each are constituted by a light source optical system 2801, mirrors 2802, 2804 to 2806, a dichroic mirror 2803, a prism 2807, a liquid crystal display device 2808, a phase plate 2809, and a projection optical system 2810. The projection optical system 2810 is constituted by an optical system including a projection lens. Although this embodiment shows an example of a three-plate type, it is not limited thereto, and a single plate type may also be available, for instance. Further, optionally, an optical system such as an optical lens, a film with a polarization

function, a film controlling the phase difference, and an IR film may be disposed at the light path indicated by an arrow in Fig. 4C.

Fig. 4D shows an example of the structure of the light source optical system 2801 of Fig. 4C. In this embodiment, the light source optical system 2801 is constituted by a reflector 2811, light sources 2812, 2813, 2814, a polarization conversion component 2815, and a condenser 2816. Incidentally, the light source optical system shown in Fig. 4D is merely an example but is not limited thereto. For example, optionally, an optical system such as such as an optical lens, a film with a polarization function, a film controlling the phase difference, and an IR film may be disposed.

As set forth above, the scope of application of the present invention is extremely wide and the present invention can be applied to electronic equipments of any field. Moreover, the electronic equipments of this embodiment can be realized even if a structure of any combination of the embodiments 1 to 5 is used.